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EXECUTIVE SUMMARY

DIGITAL SIGNAL PROCESSING TECHNIQUES FOR IMPROVED TEMPORAL RESOLUTION OF ULTRASONIC SIGNALS

S.M. Kramer
Nondestructive and Fracture Evaluation Section
Metallurgical Research Department

Most of the new ultrasonic NDE methods being developed are digital in nature and stand to benefit from digital signal processing techniques. This report describes the first step in a program to investigate the utility of various digital signal processing techniques applied to ultrasonics.

Four techniques were analysed for their ability to improve the temporal resolution of ultrasonic echoes. Increased temporal resolution allows closely spaced and near surface defects to be properly detected and characterized. Real and synthesized signals were processed with the best performance achieved with a time domain deconvolution technique which provided very good improvement in temporal resolution. Another technique, the magnitude of the analytic signal, provided no quantitative increase in time resolution, but appears to be superior to current display methods. The techniques investigated show encouraging potential for more complete utilization of ultrasonic information.

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TO: Dr. D. Mills
Director of Research
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Most of the new ultrasonic NDE methods being developed are digital in nature and stand to benefit from digital signal processing techniques. This report describes the first step in a program to investigate the utility of various digital signal processing techniques applied to ultrasonics. Four techniques were analysed for their ability to improve the temporal resolution of real and synthesized ultrasonic waveforms.

1.0 INTRODUCTION

Conventional ultrasonic NDE methods have been used effectively to detect defects and measure wall thickness in service, but are insufficient for the more complex evaluation required in crack depth measurements, defect sizing, and materials characterization. These shortcomings have spawned a variety of new ultrasonic techniques such as crack tip diffraction, synthetic aperture focusing, and spectral analysis. Many of these involve processing of the digitized ultrasonic signal, and have been made possible by the recent advances in high frequency digital signal acquisition hardware.

A program is now underway to investigate the ability of digital processing techniques to enhance the capability and reliability of ultrasonic NDE methods. This report presents a preliminary investigation of a number of digital signal processing techniques used with the intention of increasing time domain resolution. Spectral division deconvolution, time domain deconvolution, cepstral processing, and the analytic signal presentation methods are described and applied to synthetic and real ultrasonic signals.

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In many situations, improved temporal resolution will result in better ultrasonic inspections. In the crack tip diffraction method of defect sizing for instance, time resolution sets the lower limit on crack sizing ability. In normal beam pressure tube inspection, reflections from near surface defects are often obscured by the large surface reflection because of inadequate temporal resolution. It is clear that techniques which can increase temporal resolvability may be very useful.

2.0 SIGNAL PROCESSING TECHNIQUES

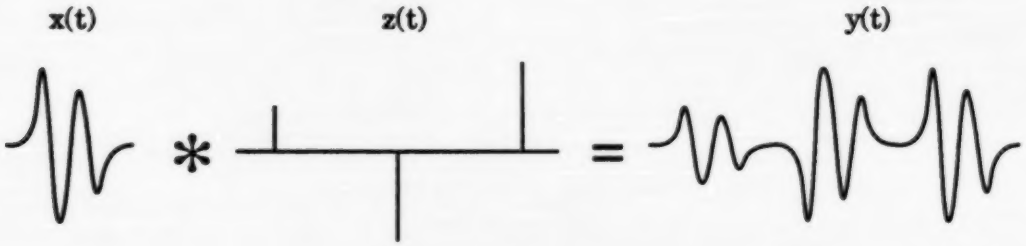
2.1 Spectral Division Deconvolution

A straightforward technique to increase the time resolution of ultrasonic signals is to increase the signal bandwidth. Any practical pulsed ultrasonic pulser/transducer/receiver system has a limited frequency bandwith response, the result of which is ringing of the ultrasonic signal. This ringing of the signal makes temporal measurements difficult, especially when ringing portions overlap and interfere. Often, because of inadequate bandwidth (and thus time resolution), what appears as a single reflection is actually a composite of two or more reflector signals which can not be adequately resolved. Thus, near surface defects may be undetectable with a normal beam inspection.

If we assume the interaction between the ingoing ultrasonic wave and reflectors in the medium is a linear process, and the transducer response to multiple signals is also linear, then the received pulse-echo signal y(t) can be represented by

$$y(t) = x(t) * z(t) \qquad (1)$$

where z(t) is a spike train representing the reflectors in the medium as a function of transit time, x(t) is the reference waveform (primary wavelet), and * indicates the convolution operation. This convolution process is shown graphically below.



The reference waveform is most often chosen as the pulse-echo signal received from a plane reflector, for this takes into account the effects of the receiving probe and the ultrasonic instrumentation.

To find the delta function reflection field (z(t)) we must deconvolve the ringing transducer and system from the received signal. Since convolution in the

time domain is equivalent to multiplication in the frequency domain, equation (1) is equivalent to

$$Y(f) = X(f)\, Z(f)$$

z(t) can now be found by dividing the received spectrum Y(f) by the reference spectrum X(f) and performing an inverse Fourier transform:

$$z(t) = F^{-1} \{ Y(f)/X(f) \}$$

While this method is simple and straightforward, it is highly susceptible to noise and spectral nulls in the reference spectrum. Since the reference spectrum X(f) is used as a divisor, low amplitude noise takes on a large relative importance, while nulls produce an infinite response.

The results of this investigation confirm these ideas; for synthetic signals (i.e. no noise), the method works well, but for experimental waveforms, the broadband noise results in poor deconvolution, an extremely elevated noise level and little improvement in resolution.

2.2 Time Domain Deconvolution

A related deconvolution method carried out solely in the time domain rather than the frequency domain has been called time domain deconvolution (TDD)[1]. TDD performs the convolution of equation (1) iteratively, using a best guess $\tilde{z}(t)$ for the unknown z(t). The resulting $\tilde{y}(t)$, an approximation of the received signal, is compared with y(t), the actual received signal, and appropriate corrections are made to $\tilde{z}(t)$. The process is repeated, gradually leading to a better approximation of y(t). When the correspondence is within prescribed limits, the $\tilde{z}(t)$ function is assumed to be a good approximation of z(t). This iterative procedure of convolution-correction-convolution is very time consuming, (taking upwards of fifteen minutes for 512 points, versus 15 seconds for the spectral division method) but the results achieved are quite good and not overly susceptible to noise. However, as in the case of spectral division, the results are highly dependent upon the assumption of delta function reflectors, and the use of an appropriate model of the basic ultrasonic wavelet.

2.3 Cepstral Domain Processing

A technique which does not rely on the foreknowledge of the shape of the reflected waveform is cepstral domain analysis (including homomorphic deconvolution). This involves the emphasis or de-emphasis of components of a signal through filtering and manipulation in the cepstral domain. The cepstrum is calculated as the discrete Fourier transform (DFT) of the log power spectrum of the signal (the DFT of the log of the square of the magnitude of the DFT of the time domain signal). Procedures carried out in the cepstral domain are nonlinear in time and so have some useful properties. How this method may be used to make accurate temporal measurements will now be described.

Consider a composite signal y(t) which is composed of a basic wavelet x(t) and a delayed echo x(t+Δt)

$$y(t) = x(t) + x(t+\Delta t)$$

The frequency spectrum Y(f) of this signal is given by

$$Y(f) = \int e^{(jwt)}[x(t) + x(t+\Delta t)]dt$$

$$= X(f) + X(f)e^{(-jw\Delta t)}$$

and the power spectrum of y(t) (i.e. $S_y(f)$) is given by

$$S_y(f) = |Y(f)|^2 = |X(f)|^2 [1+ e^{(jw\Delta t)}] [1+ e^{(-jw\Delta t)}]$$

$$= S_x [2+2\cos(w\Delta t)]$$

and is thus composed of the power spectrum of x(t) and a beat signal dependent upon the delay Δt between the primary wavelet and its echo. Taking the natural logarithm of this signal,

$$\ln[S_y(f)] = \ln[S_x(f)] + \ln[2+2\cos(w\Delta t)]$$

we are left with a function which consists of the logarithm of $S_x(f)$ and a function periodic in Δt. A DFT of this signal will produce a "frequency" spectrum of the logarithm of the power spectrum - a signal in the cepstral domain- in which the periodic nature of the beat frequency will show up as a peak at "quefrency" Δt ("frequency" in the cepstral domain is called "quefrency"). Thus the separation Δt should be apparent in the cepstral domain. Furthermore, since the $\ln[S_x(f)]$ portion of the cepstrum is usually displaced from the $\ln[2+2\cos(w\Delta t)]$ portion, "liftering" (filtering in the cepstral domain) and transformation back to the time domain will produce x(t), the primary wavelet. Once the primary wavelet has been found (or rather, approximated) an attempt to deconvolve it from the received signal can be made, resulting in the delta function reflector field. This procedure, called homomorphic deconvolution, is not simple to perform in practice due to the complexity of preserving the phase information in the transformation to and from the cepstral domain[2]. While no advance knowledge of the wavelet shape is required, the process depends on the similarity of the reflected signals, and becomes increasingly complicated when multiple reflections are present.

2.4 Magnitude of the Complex Analytic Signal

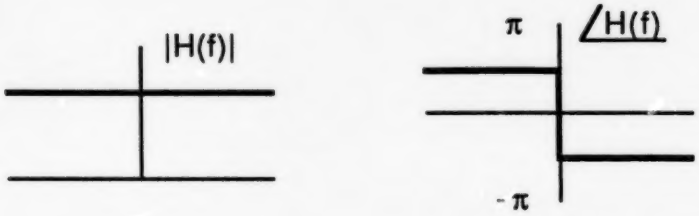
A technique which has been proposed for increasing time domain resolution[3] is the use of the analytic signal (referred to in communications theory as the "pre-envelope"). The analytic signal b(t) is defined as the complex signal whose imaginary part g(t) is the Hilbert transform of its real part x(t), i.e.

$$b(t) = x(t) + jg(t)$$

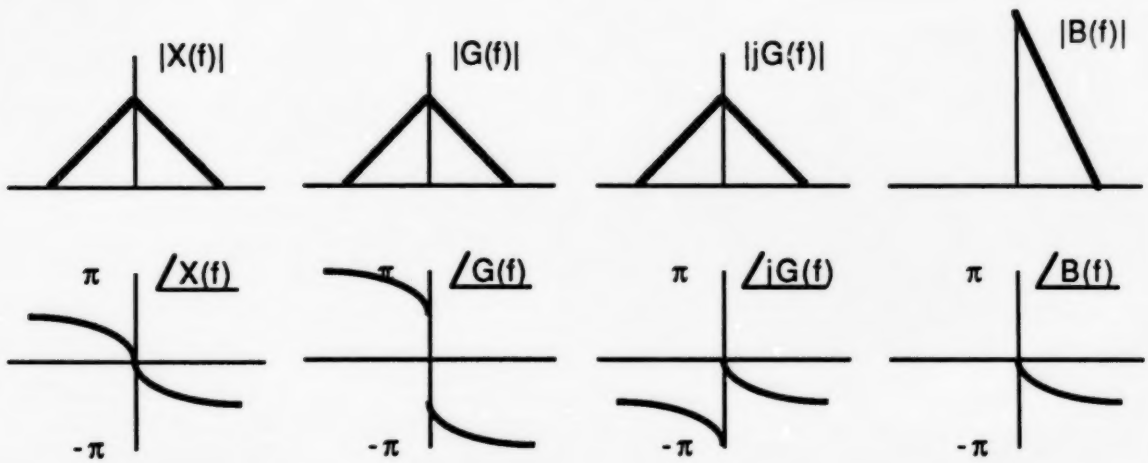
where,

$$g(t) = H[x(t)]$$

H being the Hilbert transform operator. The Hilbert transform of x(t) is simply x(t) with a phase shift of $-\pi/2$. Thus g(t) can be found by passing x(t) through the ideal $-\pi/2$ phase shifter pictured below



Thus the magnitude and phase of the resulting signal spectra are shown diagramatically below.



It is clear from the diagrams that the analytic signal spectra B(f) is identical, for positive frequencies, to X(f), but double the magnitude. Thus the analytic signal b(t) can be readily found by performing a DFT on x(t), zeroing the negative frequency components of X(f), doubling the positive frequency amplitudes, and then performing an inverse DFT.

Heyser[4] has suggested that the square of the magnitude of the analytic signal is proportional to the rate of energy arrival and as such is a good indicator of accurate interface location. Essentially, the magnitude of the analytic signal (i.e. $\sqrt{[g(t)^2+x(t)^2]}$) produces a signal which approximately traces the peaks of the rectified waveform. No additional bandwidth has been added so there can be no increase in time resolution *per se*, but sometimes this presentation can clarify certain features that were obscured in the normal bipolar waveform. In addition, a unipolar signal has been created without the information loss inherent in traditional analogue rectification and smoothing processes.

3.0 RESULTS

The techniques described above, have been implemented in software and applied to three specific cases of simulated and real ultrasonic signals to gauge their usefulness and limitations.

Case 1 : A simulated signal composed of three identical broadband ultrasonic pulses with peak amplitudes in the ratio 1:-10:100 (figure 1a).

i) The absence of noise and the similarity of the signals permits a perfect deconvolution through spectral division (figure 1b) using any one of the three as the reference waveform. The amplitude and temporal relationships are preserved exactly, along with the signal polarity. This result represents the ideal case: the deconvolution resulting in a delta function reflection field.

ii) The cepstrum of figure 1c accurately indicates the separation of signals β-γ, and α-γ, but the α-β separation "beat frequency" is not apparent. In addition, a large processing artefact is present. Note that the time scale of figure 1c is expanded by a factor of two.

iii) Figure 1d shows the magnitude of the analytic signal. The temporal relationships have been preserved but not enhanced, and noise introduced by the algorithm is of the order of the small α signal. Polarity information is lost, but this has the advantage of ensuring proper temporal measurements in the case of inverted reflections.

Case 2 : A simulated signal composed of three equal amplitude pulses, two of which (α,β) have overlapped (figure 2a).

i) As previously, the spectral division deconvolution works perfectly in the absence of noise (figure 2b).

ii) The cepstrum of this signal (figure 2c) accurately indicates the separation of α-γ, and β-γ, and the harmonics of the separation time α-β are apparent, although interpretation of the cepstrum is not straightforward.

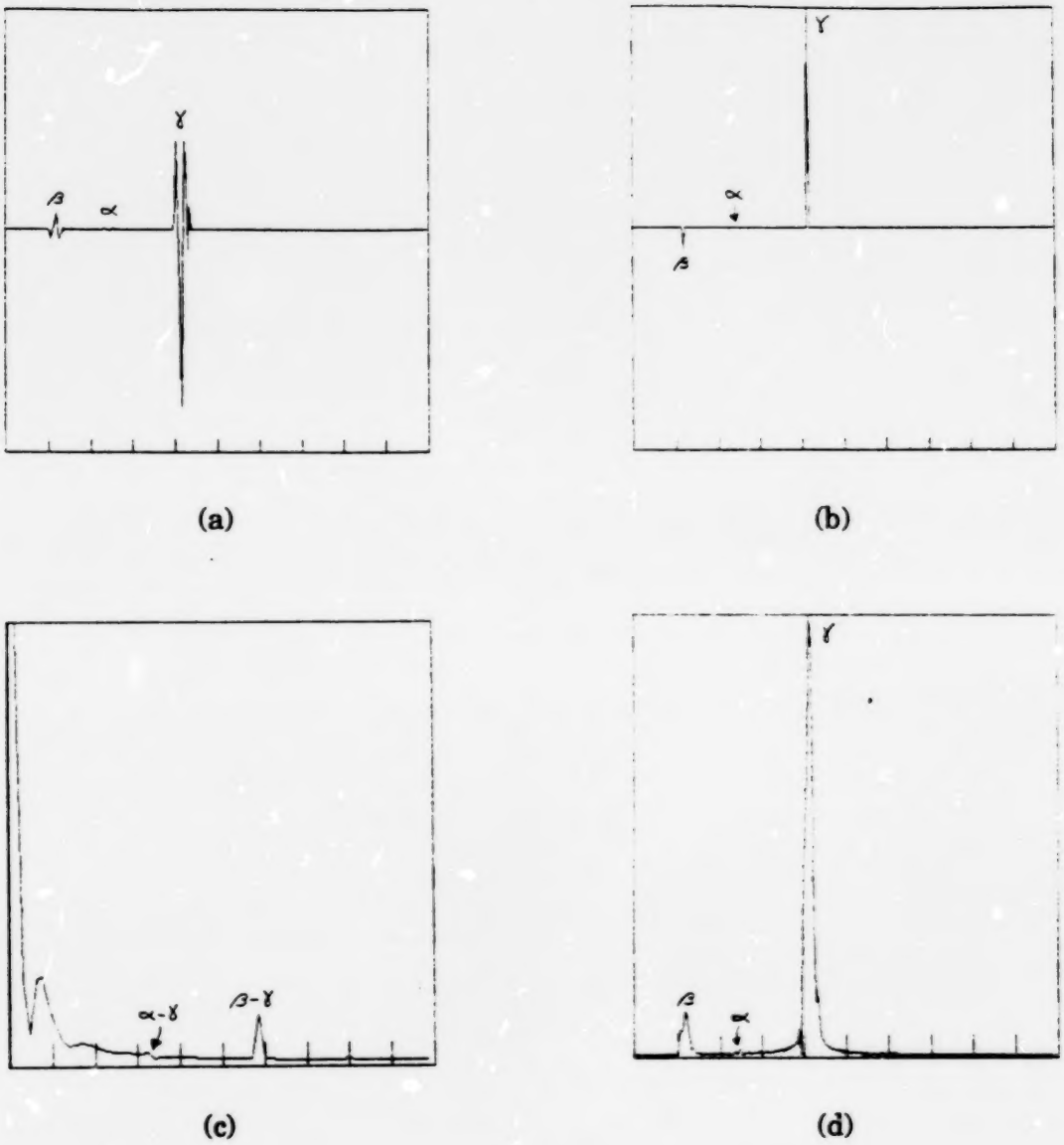
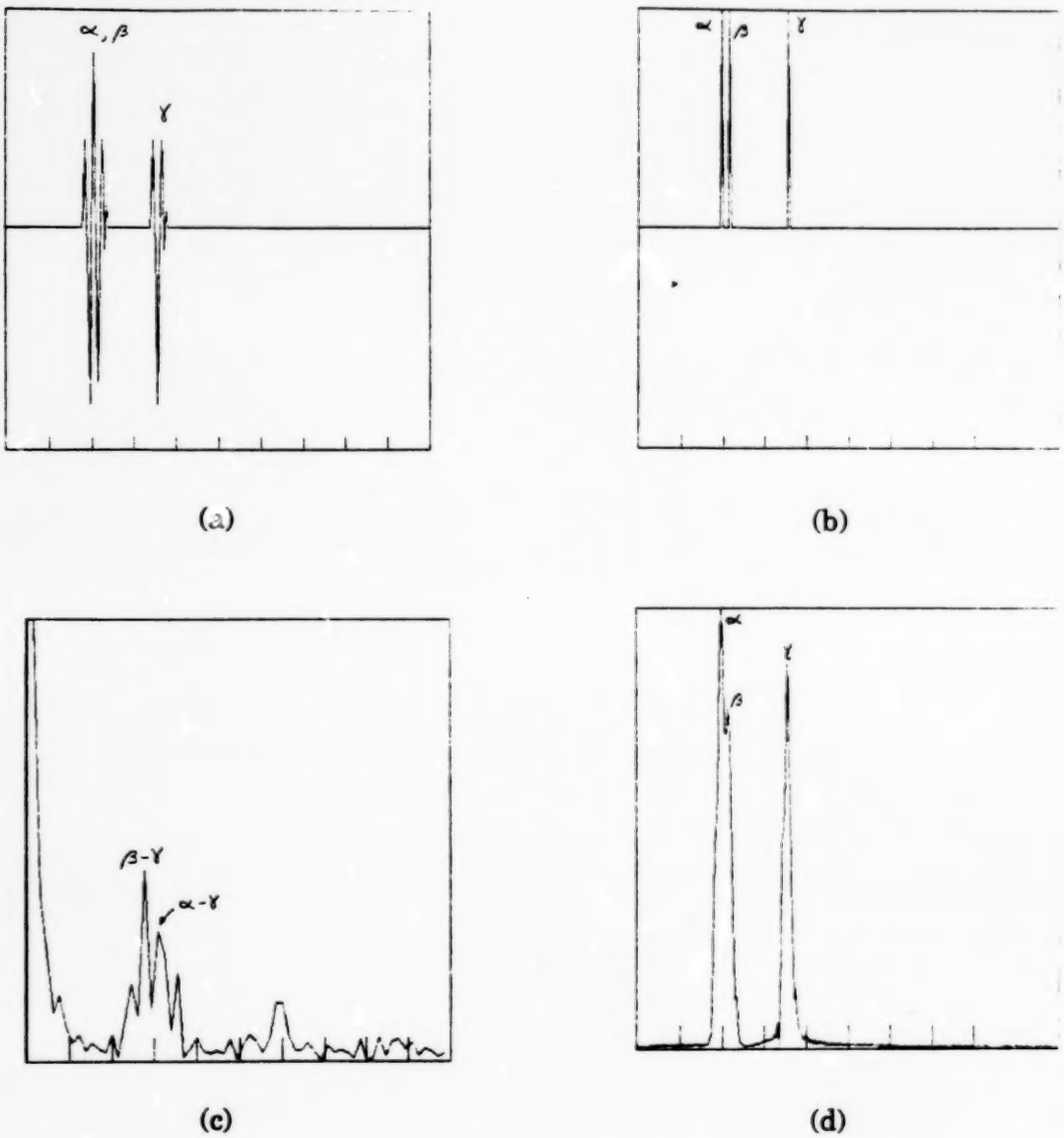


Figure 1 Synthetic signal composed of 3 similar pulses with amplitude relationship 1:-10:100 (α,β,γ). (a) original unprocessed waveform, (b) after spectral division, (c) cepstral domain (horizontal scale expanded by a factor of 2), (d) magnitude of the analytic signal.



(a) (b)

(c) (d)

Figure 2 Synthetic signal composed of 3 identical pulses with the first two interfering, (a) original unprocessed waveform, (b) after spectral division, (c) cepstral domain (horizontal scale expanded by a factor of 2), (d) magnitude of the analytic signal.

iii) Temporal measurements from the magnitude of the analytic signal (figure 2d) result in inaccuracies as the α and β peak tend to draw each other closer together. The two-component nature of the α,β interference is perhaps apparent, but no more so than in the original time domain signal.

Case 3 : The signal from an outside surface machined notch using two 45° shearwave probes operating in pitch-catch mode from inside a Zr pressure tube section (figure 3a). The two apparent signals are α, the diffraction from the notch tip, and β, the Zr/water interface reflection.

i) Figure 3b shows the result of simple spectral division on the signal using the β reflector as a reference. The modest noise level present in the original signal is highly intensified through the division process. Two main reflectors are apparent with the appropriate amplitude and temporal relationship, but there are also many apparently spurious spikes in the vicinity of the diffracted signal α.

ii) The noise tends also to corrupt the cepstrum (figure 3c), with one major peak indicating the appropriate delay between pulses α and β. The signal to noise ratio in the cepstrum domain is considerably reduced from the original time domain signal.

iii) The magnitude of the analytic signal (figure 3d) apparently adds little further information, although there may be an indication of something significant at $\alpha 2$.

To perform the time domain deconvolution algorithm some manipulation of the signal is required. The frequency content of this signal is primarily below 32 MHz and completely below 64 Mhz, thus at a sampling rate of 256 MHz the signal has been oversampled. A 4-point moving average was applied and a smaller data file was created by "decimation-in-time" or "subsampling" - discarding redundant data points to reduce the frequency ambiguity. The signal was gated and moved to the right half of the data file (as required by the algorithm), and time domain deconvolution was performed.

iv) Figure 4a shows the result of twenty iterations of the TDD algorithm, indicating two separate scattering sites ($\alpha 1$ and $\alpha 2$) at the notch tip, separated in time by 0.03 μs transit time.

v) Re-evaluating the cepstrum of figure 3c, a quefrency (cepstral frequency) of the appropriate delay $\alpha 2$-β is apparent though not striking. A second local peak on the magnitude of the analytic signal (figure 3d) also occurs at the corresponding position.

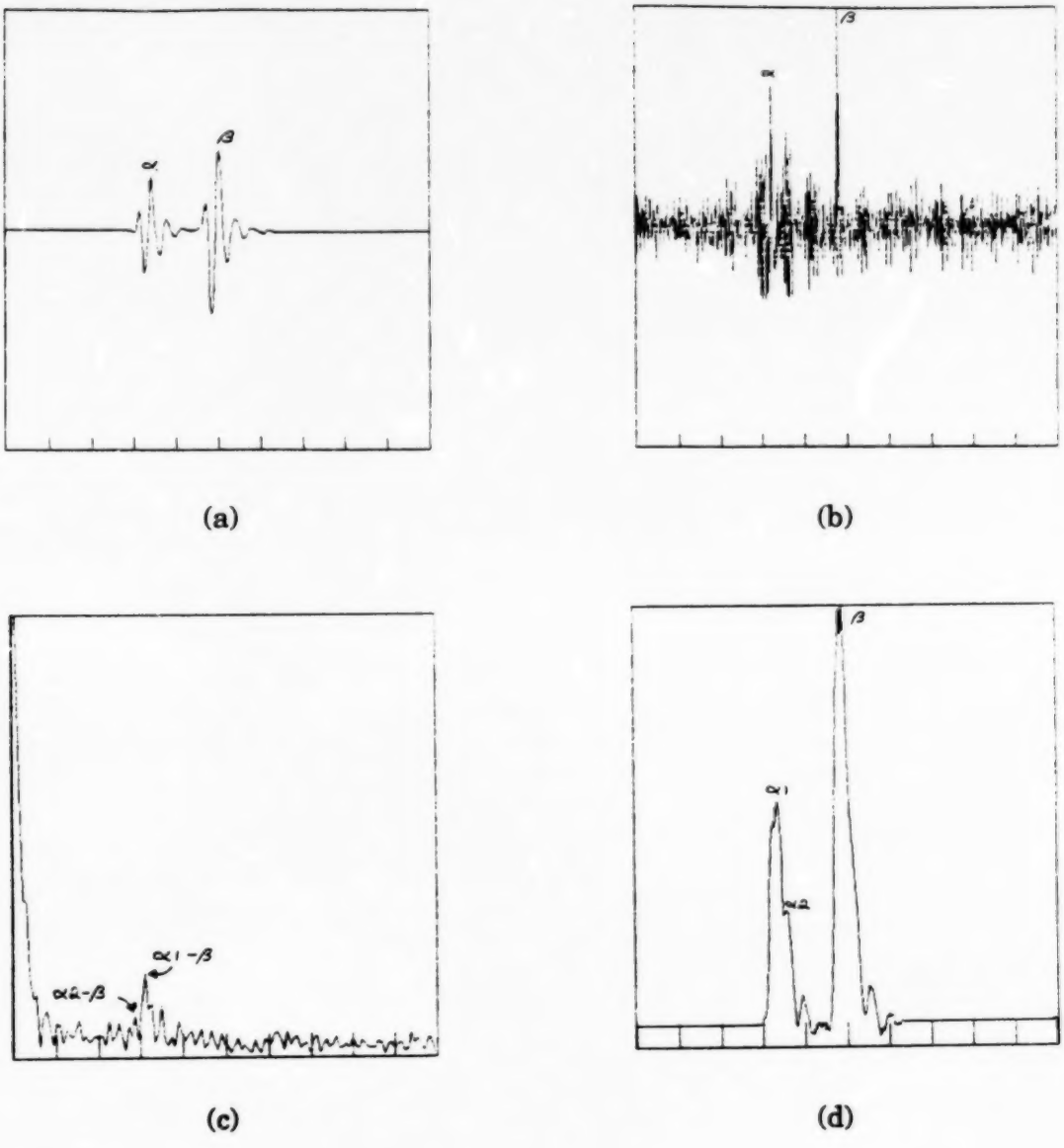
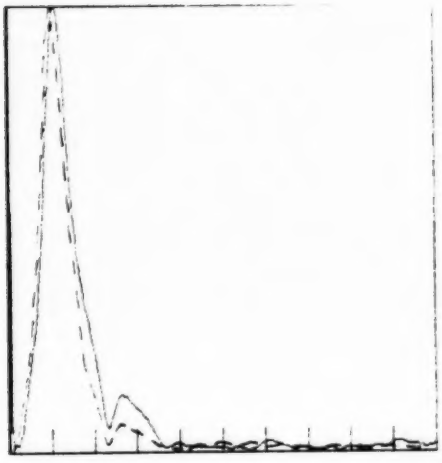


Figure 3 Real ultrasonic waveform composed of a diffracted signal (α) and a reflected signal (β), (a) original unprocessed waveform, (b) after spectral division, (c) cepstral domain (horizontal scale expanded by a factor of 2), (d) magnitude of the analytic signal.

(a)



Frequency

(b)

Figure 4 (a) result of 20 iterations of the time domain deconvolution algorithm on the waveform in figure 3a. Note that the diffracted signal α is resolved as two components, α1 and α2.

(b) frequency spectrum of α (——) and β (- - -), the two components of figure 3a.

vi) Figure 4b shows the magnitude of the frequency spectra for the notch diffraction and the interface reflection signals (from figure 3a) isolated from one another. The larger proportion of higher frequencies seen in the crack tip signal is indicative of interference between two similar signals as one might expect from two scattering (or diffracting) centres. Note that the entire tip diffracted spectrum seems shifted up in frequency as well.

4.0 DISCUSSION AND CONCLUSIONS

The implementation and testing of these procedures using actual ultrasonic signals as well as synthetic data allows a number of conclusions to be drawn concerning their operation.

The simple spectral division method of deconvolution is perfectly valid under ideal noiseless conditions, but breaks down in practical situations. A number of extensions to this procedure have been implemented in seismic analysis, including spectrum regularization and extrapolation[5], which attempt to avoid the problems of spectral nulls and noise.

The time domain deconvolution method works quite well in perfoming the deconvolution and thus increasing temporal resolution. The ultimate resolution of the technique is not limited by the system or material bandwidth, but by the sampling rate, and appears to operate well in the presence of moderate noise levels. The incremental, iterative operation of the algorithm in the time domain results in high stability but also entails extended processing time. Unfortunately, the valuable information concerning reflected signal polarities is lost in the process. Nonetheless, this technique may be appropriate for the crack tip diffraction method where accurate temporal measurements are required, and processing speed is not critical

Analysis of the cepstral domain is not straightforward for any but the simplest signals. The spectral "whitening" effect of the logarithm operation tends to enhance the response to small reflectors but also to noise. To fully exploit the potential of homomorphic deconvolution would require much further work, but the technique is perhaps more suited for situations in which the reference waveform is unknown.

The magnitude of the analytic signal, while providing no real increase in resolution over the unprocessed signal, appears to be easier to interpret in cases of overlapping waves. Furthermore, this presentation provides a unipolar, smoothly varying signal without the loss of resolution inherent in simple rectification and filtering. Since the magnitude of the analytic signal is proportional to energy arrival, it would likely be a good display method for digital B-scans.

A number of potential benefits seem apparent from the techniques investigated, and they have also indicated areas in which further work is necessary. Digital filtering techniques, applied in the time domain, should be

able to accomplish much of what has been done through spectral means, at much higher speeds. Predictive deconvolution, a successful method of seismic analysis, has the potential to produce highly resolved signals quickly. These and other techniques will be investigated in future work.

Recommended:

J.A. Baron
Section Head
Nondestructive and Fracture Evaluation Section
Metallurgical Research Dept.

Prepared:

S.M. Kramer
Engineer
Nondestructive and Fracture Evaluation Section
Metallurgical Research Dept.

Approved:

J. Brown
Manager
Metallurgical Research Dept.

SMK:SEH

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